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6. AUTHOR(S)
Seegers, Bryan J.
Shreiner, David G.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
M-DOT INC.
3416 South 48th Street, Suite 2
Phoenix, AZ 85040

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During the performance period, a heavy-wall ground-test thrust spoiler/reverser was designed, fabricated and tested on a Sundstrand TJ-90 expendable turbojet engine. Maximum forward corrected thrust attained was 91.8 lbs. and maximum reverse corrected thrust was 68.2 lbs. Thrust from a circular calibration nozzle under the same conditions was 95.4 lbs. The reverser consisted of bifurcated Hastelloy-X exhaust duct with machined Hastelloy-X nozzles and deflectors at each exit. The deflectors were driven by an electric servo actuator through a rod-end bearing linkage assembly. Actuation time from full forward to full reverse was 0.5 seconds. At the conclusion of the program, a layout of a flight-weight reverser was created.

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FINAL REPORT

for

THRUST SPOILER/REVERSER SYSTEM FOR A LOW-COST-EXPENDABLE TURBOJET ENGINE
CONTRACT NO. DAAH01-93-C-R096

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CONTRACT NO. DAAH01-93-C-R096

CONTRACT PERIOD: January 23, 1993 to September 10, 1993

Report Date: October 25, 1993

Submitted by:

Bryan J. Seegers
President, M-DOT INC.

M-DOT INC.
3416 South 48th Street, Suite 2
Phoenix, Arizona 85040

FUNDED BY:

U.S. ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA

MONITORED BY:

Dr. Jay S. Lilley
U.S. Army Missile Command
ATTN: AMSMI-RD-PR-E/LILLEY
Redstone Arsenal AL 35898-5280

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1.0 EXECUTIVE SUMMARY

A thrust reversing system employed on a small turbojet-powered missile would afford improved response time for rapid changes in vehicle flight speed by eliminating the requirement for time consuming throttle transients. For this program, M-DOT designed, fabricated and tested an electrically-actuated bifurcated thrust spoiler/reverser for use on the Sundstrand TJ-90 expendable turbojet. The system demonstrated 87.8 physical lbs. of forward thrust, 65.3 physical lbs of reverse thrust and a transition time of 0.5 seconds from full forward to full reverse thrust. Weight of the complete heavy-wall system was 12.5 lbs.

Main components of the system were:

- **Bifurcated exhaust duct.** This consisted of compound-formed Hastelloy-X sheet-metal duct with machined V-band-clamp flange at the inlet and machined bolt flanges at each exit. The duct transitioned from a circular cross section at the inlet to rectangular at the exits.

- **Exhaust deflector nozzles.** These consisted of machined Hastelloy-X rectangular housings each with a forward and rearward facing rectangular exit. Contained within each housing was a machined and welded deflector plate mounted on graphite bearings. The deflector plates rotated through an angle of 46° to transition from full forward to full reverse thrust.

- **Electric servo actuator and linkage.** The reverser was actuated by a Tonegawa Seiko model SSPS-102 electric servo. The servo output-shaft bellcrank was connected to the deflector bellcranks by threaded push rods with rod-end bearings at each end. The servo was mounted in a stainless steel container which had provision for forced-air cooling.

- **Servo controller.** The servo was remotely controlled using a hand-held driver purchased from Condor RC Specialties. A joystick on the driver was used to position the servo.

All hardware, except for servo actuator and driver, was designed and fabricated at M-DOT. The deflector and linkage configuration was simulated using mylar models prior to design of metal parts. Exit area of the rectangular nozzles was based upon area of a Sundstrand calibration nozzle supplied with the TJ-90 engine. Area was fine tuned during testing by bending the sheet-metal side walls of the nozzle. When laying out the two-dimensional nozzle and deflector plate, the intent was to realize a axial divergence angle as narrow as possible to maximize the axial thrust component in both directions. This was done at a slight sacrifice in $\Delta P/P$ for the duct with a resulting reduction in performance. The deflector plate was designed to have minimal

moment about the pivot axis due to pressure forces. The electric servo actuator provided a means of remotely controlling the reverser. Commercially available radio-controlled aircraft servos were studied. The Tonegawa Seico was chosen because it is one of the most powerful actuators on the market with a stall torque of 109 inch lbs. Position of the actuator was controlled one of two ways during testing. Initially, a small hand-held positioner was used which featured a joystick. During testing however, failure of the servo-motor amplifier board, necessitated construction of a simple polarity control with double-throw momentary toggle switch. This allowed position control by simply applying power to the motor until the desired position was reached. The amplifier board was eventually replaced.

The duct was fabricated from 0.063 inch thick Hastelloy-X sheet. Duct walls were compound formed using a hydraulic press and TIG welded together. The inlet V-band flange was machined from Hast-X plate as were the rectangular flanges at the exit. High-temperature A-286 bolts were used to hold the exit nozzles in place.

The test engine was a government-owned prototype TJ-90 turbojet engine manufactured by Sundstrand Power Systems of San Diego CA. Modifications were made to the engine at M-DOT to remove the existing bifurcated duct and incorporate a circular duct with V-band flange. The government supplied a thrust calibration nozzle and exhaust instrumentation duct with the TJ-90.

Bench testing was conducted on a cold-flow stand using electric blowers to supply air to the duct. Testing was conducted to identify leak paths, verify exhaust direction and measure transition time. Transition time measured during cold cycling tests was 5 seconds for 5 complete cycles or 0.5 seconds from full forward to full reverse.

Engine testing was conducted on an M-DOT-owned thrust stand. Instrumentation consisted of type K (chromel-alumel) thermocouples at station 5.0 (turbine exit), static pressure at station 3.0, engine shaft speed, bearing temperature and bidirectional thrust. Fuel was Jet-A aviation kerosene. Prior to testing the reverser, baseline engine performance was measured using the calibration nozzle supplied by Sundstrand. Corrected thrust with the calibration nozzle at 100,000 rpm, 87° F ambient temperature and 1528° F measured turbine exit temperature was 95.4 lbs.

Maximum forward corrected thrust was 91.8 lbs. at 1611 ° F turbine-exit temperature. Maximum reverse corrected thrust was 68.2 lbs. at 1572 °F turbine-exit temperature. If cosine error due to the reverse exit angle of 15° is corrected for, actual corrected nozzle thrust becomes 70.6 lbs. The reverser was successfully cycled at 70K, 80K, 90K, and 100K rpm engine speed.

To help determine control requirements on future applications, deviation in station 3.0 pressure and engine speed was measured at a fixed fuel flow at several points during a transition. These data were used to calculate a change in effective nozzle area. This value was 2.8% over the complete operating range.

2.0 OBJECTIVE

The overall objective of the program was to design, fabricate and demonstrate a heavy-wall ground-test thrust spoiler/reverser for an expendable turbojet.

3.0 CONCLUSIONS

Based upon test results, the following conclusions can be reached:

- It is possible to obtain a significant amount of reverse thrust for braking from a small bifurcated thrust reverser. 71.5 % reverse thrust was obtained from the prototype unit.

- It is possible to design a thrust reverser to have a reasonably constant back pressure throughout transition such that an electronic control will not have difficulty maintaining engine speed.

- Great care must be taken on future designs to accurately calculate steady-state and transition temperature of reverser components in order to prevent lockup due to differential expansion. It was estimated from visual observation of the radiation color that the deflector plates assumed a temperature more than 100°F hotter than the duct. This was apparently the cause of lock up that was experienced on several occasions at high throttle settings. The problem was resolved by removing material that had witness marks from rubbing.

- Graphite is a suitable high-temperature bearing material for the deflector plates.

4.0 RECOMMENDATIONS

The following is recommended if future development is to be done on the thrust reverser:

- Thin-wall machined castings in Inconel 713, Hastelloy-X or equivalent high-temperature material should be investigated if a flight-weight unit is to be developed. The castings would comprise the nozzles and the deflector plates. To keep weight low the cast nozzles would be fixed to the bifurcated pipe by vacuum-nickel-brazed slip joints.

- To keep weight and volume low, a rare-earth permanent-magnet motor should be considered for the servo actuator. Minimum stall torque should be at least 125 inch lbs.

- To reduce leakage around the deflector plates, some form of sprung sheet-metal wiper seal should be employed.

5.0 BACKGROUND

A principle reason why some missiles employ turbojet engines as power plants is the capability of controlling missile speed by throttling the engine. An inherent problem of turbojet propulsion is the high response time required for changes in power. If a missile were to require a sudden change in flight speed, a method of rapidly redirecting engine exhaust while the engine remained at high power may be required.

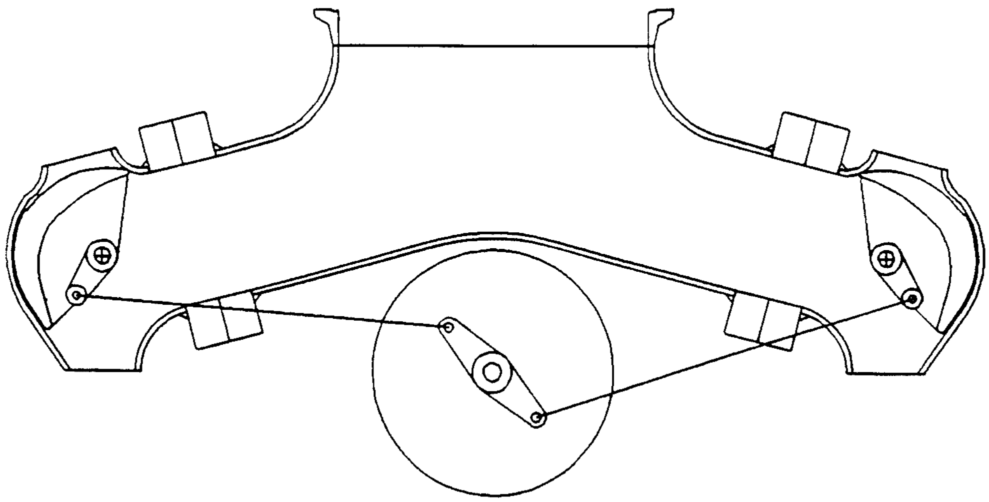
Employment of a thrust reversing or vectoring system on a turbojet powered missile would afford more rapid change in flight speed.

5.1 Statement of Work

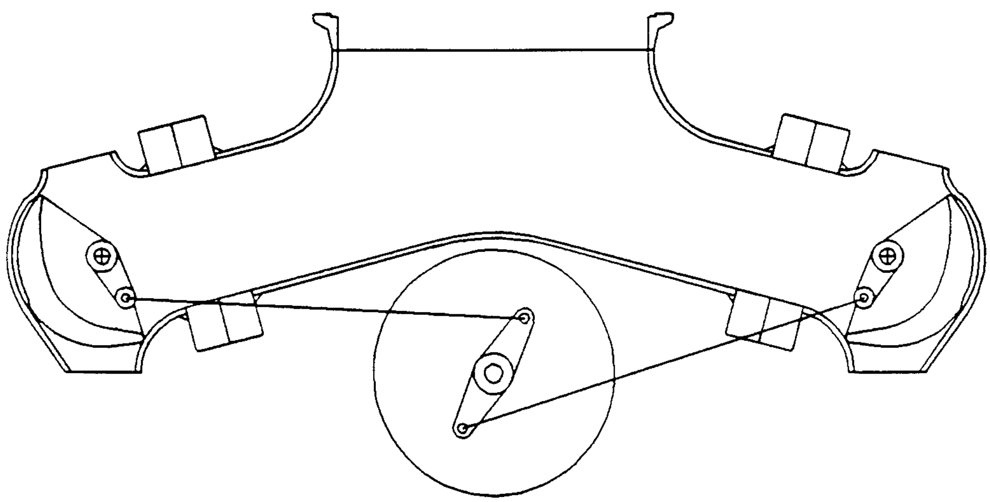
M-Dot proposed to design, construct and test an electrically-actuated heavy-walled thrust-reversing system with controller for application on the Sundstrand TJ-90 expendable turbojet engine. Upon completion of testing, a layout of a flight-weight system would be created for detailing, fabrication and testing during Phase II.

5.2 Background on the Phase I Reverser design

M-DOT sought during Phase I to produce a heavy-wall proof-of-concept prototype of a twin-nozzle thrust reverser suitable for application on a bifurcated exhaust system. The design was based on a concept illustrated in Figure 1 whereby each tailpipe exit has two ports which can be selectively covered by an arc-shaped deflector plate. It was believed that the nozzle ports and deflector plates could be configured to maintain a constant back pressure regardless of deflector position. This would allow partial braking during flight and would reduce controller work load since the engine would not have a tendency to change its operating point during transition. Figure 2 depicts the TJ-90 with reverser installed on the M-DOT thrust stand.



FULL FORWARD THRUST



FULL REVERSE THRUST

Figure 1 - Layout of reverser nozzle and deflector showing principle of operation

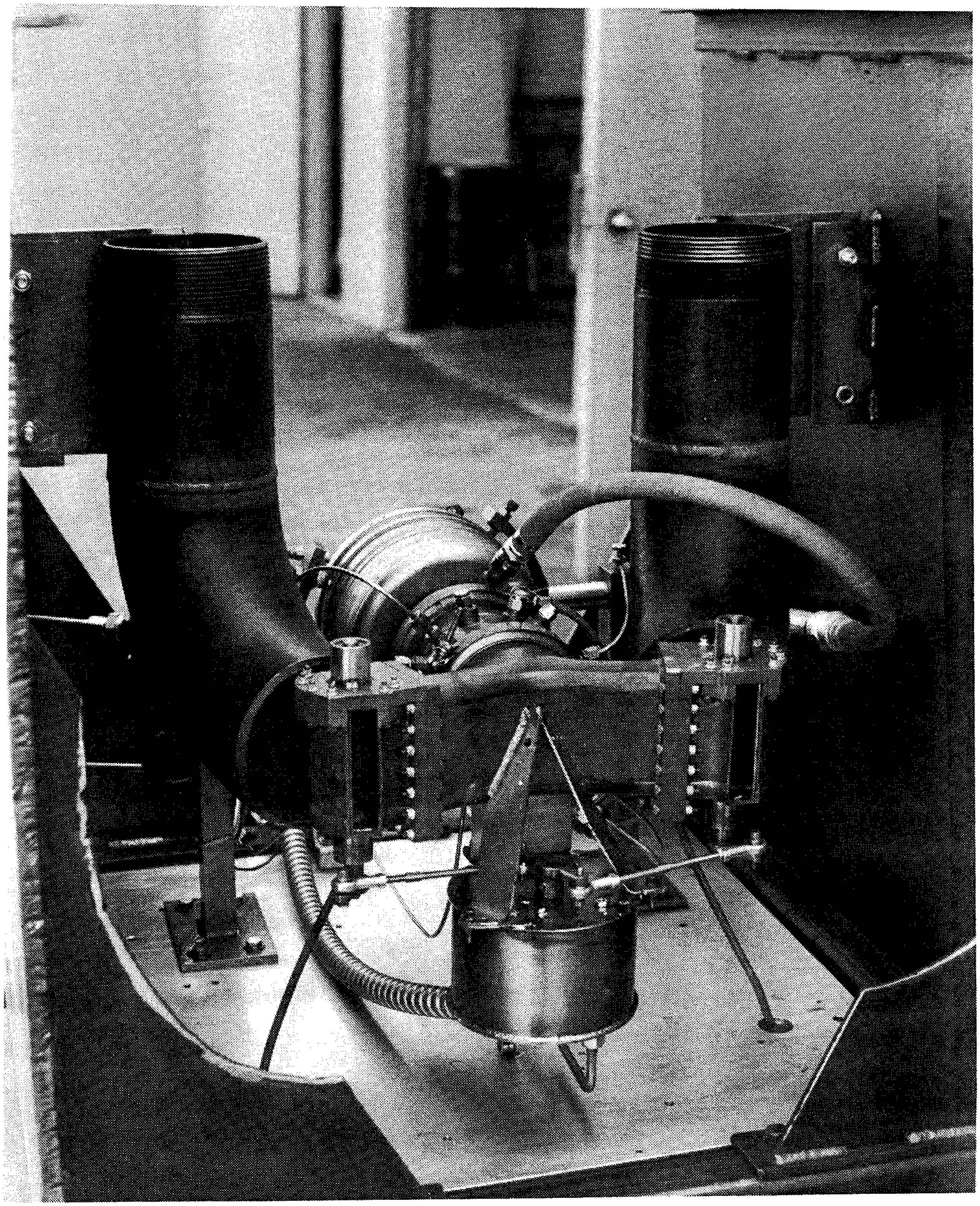


Figure 2 - TJ-90 with reverser installed on thrust stand.

Duct - A fabricated sheet-metal duct design was chosen because of M-DOT experience with this fabrication method. 0.063 inch thick sheet stock was chosen for the duct walls for robustness while still maintaining easy formability. A machined flange was placed at the inlet to provide an accurate gas-tight fit to the V-band flange on the engine. To maintain an accurate gas-tight fit at the interface between the duct and exit reversing nozzles, and to allow removal of the nozzle assemblies for modification or replacement, ⅜ inch-thick bolted flanges were employed. These flanges were stress relieved and machined after being welded to the duct to guarantee a gas-tight seal. High-temperature A-286 bolts were used to hold the exit nozzles in place.

Exit Nozzles - The exit nozzles were a welded assembly of machined and sheet metal parts. Top and bottom pieces were machined from plate and the side walls were cut and formed from sheet metal. A rectangular machined flange was welded to each nozzle inlet for assembly to the duct.

Exhaust deflector plates - Each deflector plate was designed as a five-piece welded assembly. The curved airfoil-shaped side plate was machined from solid plate stock. 0.09 in. thick sheet-metal top and bottom plates were welded to the side plate and served as anchors for the pivot shafts. Axles were welded to the top and bottom plates. To permit assembly, each nozzle featured a removable bolted cover plate. This plate supported the upper bearing carrier.

Bearings - To permit operation at high temperature, graphite bushings were employed on the deflectors.

Linkage assemblies - Linkage rods consisted of commercially available aircraft rod-end bearings connected by No. 10 threaded rod. Length of each link had to be individually adjusted to ensure that the right and left deflector plates seated simultaneously in the forward and reverse positions.

Servo actuator - To allow remote actuation of the reverser, a commercially available model aircraft servo was purchased. It was anticipated that stiction of the mechanism might occur due to thermal distortion so a large servo designed for use on military and commercial remotely piloted vehicles was selected. The Tonegawa Seiko model SSPS-102 heavy-duty servo was chosen. Room-temperature compressed air was piped into the servo housing during operation to remove heat.

Servo controller - Actuator position was controlled remotely using a hand-held joystick controller. The controller generated a 20 Hz, square-wave pulse train. Position was controlled by varying the width of each pulse between 1 to 2 milliseconds.

5.3 Working linkage model

To help visualize operation of the mechanism and to ensure that the deflector plate/nozzle configuration met requirements for sealing and constant exit area during transition, accurate layouts of components were drawn, cut out of polyester and assembled to form a working mechanism.

5.4 The Sundstrand Power Systems TJ-90 Engine

The TJ-90 expendable turbojet engine is derived from the earlier Gemjet which, in turn, was derived from the Sundstrand Turbomach Gemini T-20G-20 auxiliary power unit. Sundstrand Turbomach received a contract in 1986 from the U.S. Army Missile Command (MICOM) to provide a turbojet engine rated at 40 lbs thrust for use on the FOG-M missile. This model was scaled into the TJ-90 which is rated at 107 lb thrust at 103,000 rpm. This family of engines is characterized by the single piece "monorotor" (compressor impeller and turbine rotor in a single piece casting) and "monostator" (compressor diffuser and turbine nozzle in a single piece casting). Figure 3 below is a cross section of the TJ-90 with the reverser installed.

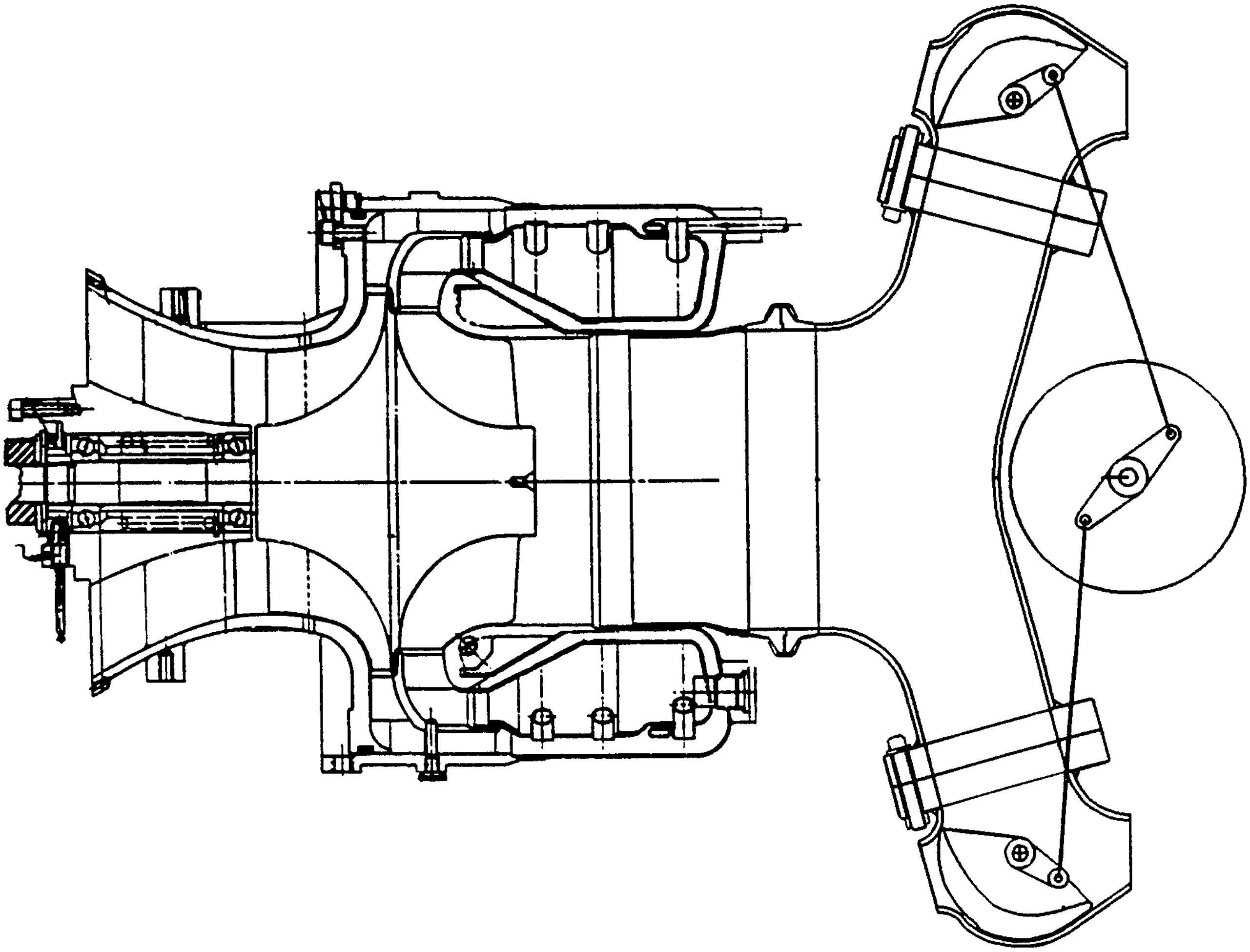


Figure 3 - Sundstrand TJ-90 with prototype reverser installed

6.0 BASIC RESEARCH AND HARDWARE DESIGN

6.1 Basic Research

The basic research portion of the program consisted of investigation into commercially-available servo actuator systems, high-temperature duct materials, and high- temperature bearing materials.

6.1.1 *Actuators* - It was desired to employ an electric gearmotor-driven actuator on the prototype unit to allow remote actuation and to gain experience with this type of actuator. Several distributers of industrial-grade servo actuation systems were contacted. All had products adequate for the application but systems were priced beyond the means of the Phase I buget. Condor RC specialties of Cost Mesa, CA was contacted because it was known they specialized in the sale of RPV/UAV servo systems. They had two systems of sufficient torque, both manufactured by Tonegawa Seiko of Japan. The SSPS-102 was chosen because it had a highest response rate. It has the following specifications:

Starting or stall torque	109 inch lbs.
Rated continuous torque	17.4 inch lbs.
Total travel	± 45°
Travel speed (minimum)	0.7 sec per 90°
Input power	11 to 14 VDC
Weight	18 oz.
Signal input	Standard R/C positive pulse-width modulation @ +5 V, 20 Hz, 1 to 2 millisecond duty cycle.

The servo featured a plastic casing. To protect it from radiant heat from the exhaust duct, it was housed in a fabricated stainless-steel container which also served as the mount. Condor also supplied the controller for the actuator.

6.1.2 *High-temperature duct materials* - Exhaust temperature of the TJ-90 can be as high as 1650 °F at maximum thrust. Basic research into suitable materials was conducted. In addition to temperature capability, weldability, formability and machinability were considered. Hastelloy-X was chosen because it was the easiest to form of all materials considered.

6.1.3 *High-temperature bearing materials* - Sources of aerospace and EDM grade graphite were investigated. EDM grade was chosen because it was inexpensive and locally available.

6.2 Hardware Design

The goal in designing the duct and nozzles was to achieve maximum possible thrust by minimizing total pressure losses. Duct area

was kept as large as possible upstream of the nozzles to reduce total pressure losses. When laying out the two-dimensional nozzle and deflector plate, the intent was to realize a axial divergence angle as narrow as possible to maximize the axial thrust component in both directions. This was done at a slight sacrifice in $\Delta P/P$ for the duct with a resulting reduction in performance. The deflector plate was designed to have minimal moment about the pivot axis due to pressure forces. The bifurcated duct transitioned from a circular cross section at the inlet to rectangular where the nozzle assemblies bolted on. Area reduction ratio in the nozzles was 2.1 to 1. Total nozzle exit area was calculated to be 4.43 $in.^2$ at an operating temperature of 1600 °F. Parts requiring high accuracy to prevent leakage such as flanges and nozzle sealing surfaces were machined from Hastelloy bar and plate stock. Other parts were fabricated from 0.063 inch thick Hastelloy-X sheet.

It was desired to make the Phase I configuration resemble the flight-weight configuration as closely as possible so basic outline dimensions of the existing Sundstrand bifurcated duct were copied. The actuator was placed equidistant between the nozzles in the location presently occupied by the start cartridge. This was done to ensure symmetrical operation of left and right deflectors.

A dimensionally accurate layout of the proposed reverser configuration was generated to visualize operation and fine tune the shape of the nozzle and deflector. Several deflector configurations were drawn on Mylar drafting film, cut out and pinned to the layout through the pivot point so that they could be rotated from forward to reverse. The chosen configuration was then modeled on Autocad to ensure accurate dimensioning of the final drawing. The linkage was also modeled in this manner.

To permit operation at high temperature, graphite bushings were employed on the deflectors. To prevent lock up due to differential expansion between the graphite and steel pivot shafts, the bushing bore was 0.015 in. larger than the pivot shaft. In addition, the bushings were slit to provide a fracture site if lock up occurred.

6.3 Laboratory Fixture Design

A cold-flow test rig was designed to evaluate reverser operation prior to engine installation. It consisted of stainless-steel plenum with three inlet ports to receive air from three industrial vacuum cleaner motors. The rig was mounted to an existing turbojet test stand.

6.3.1 Test Stand Adapters

Hard engine mounts were designed to attach at the engine casing.

Vertical struts were used to position the engine center-line the proper distance from the thrust platform pivot. Configuration of the support is plainly visible in Figure 4.

6.3.2 Starting System

Start air was supplied by a 10 HP compressor with 80 gallon receiver tank. Air lines to the test stand were plumbed with 3/4 inch schedule 40 pvc pipe. A 1/2 inch ball valve was used to control air delivery.

7.0 HARDWARE FABRICATION

All hardware was manufactured at M-DOT. Construction details follow.

7.1 Bifurcated Exhaust Duct

To fabricate the exhaust duct, a wood plug was machined that duplicated the interior wall profile. This form was used to make Hydroforming dies from gypsum cement. Hastelloy-X sheet was initially hydroformed into the dies using a hydraulic press. The resulting shells were trimmed and formed around a machined aluminum master using a hammer. A piece of flat sheet was cut out and bent to form the aft wall. Rectangular flanges at the exits were laid out on ⅝ inch Hastelloy plate and milled. The V-band flange for the inlet was turned from 4 inch diameter barstock. The entire assembly was TIG welded together and stress relieved.

7.2 Exit Nozzles

Each exit nozzle was comprised of: machined top and bottom housings, single curved side walls made from 0.063 sheet, machined bearing carriers and a machined rectangular bolt flange. The entire assembly was TIG welded and stress relieved. Final sizing of each nozzle was done on the test stand using pliers to deflect the sheet-metal side walls. During testing, a 0.063 thick sheet metal strip was welded to the interior of the nozzle exit to reduce area. The original machined area of both exit nozzles was 4.56 inches. This corresponded to the area of the Sundstrand calibration nozzle. During testing, the sides of the nozzle openings were bent with pliers to adjust area to obtain the desired operating temperature. Also during testing, 0.063 thick sheet doublers were welded to one side of the nozzle wall to reduce area. Both of these features can be seen in Figure 7. The final estimated physical area based on both modifications is 4.43 sq. in. This value is less than the area of the calibration nozzle by nearly 6 %. This can be partly explained by gas path leakage out the reverse nozzles during forward thrust operation. This leakage also helps explain why forward thrust was more than 4% less with the reverser than with the calibration nozzle.

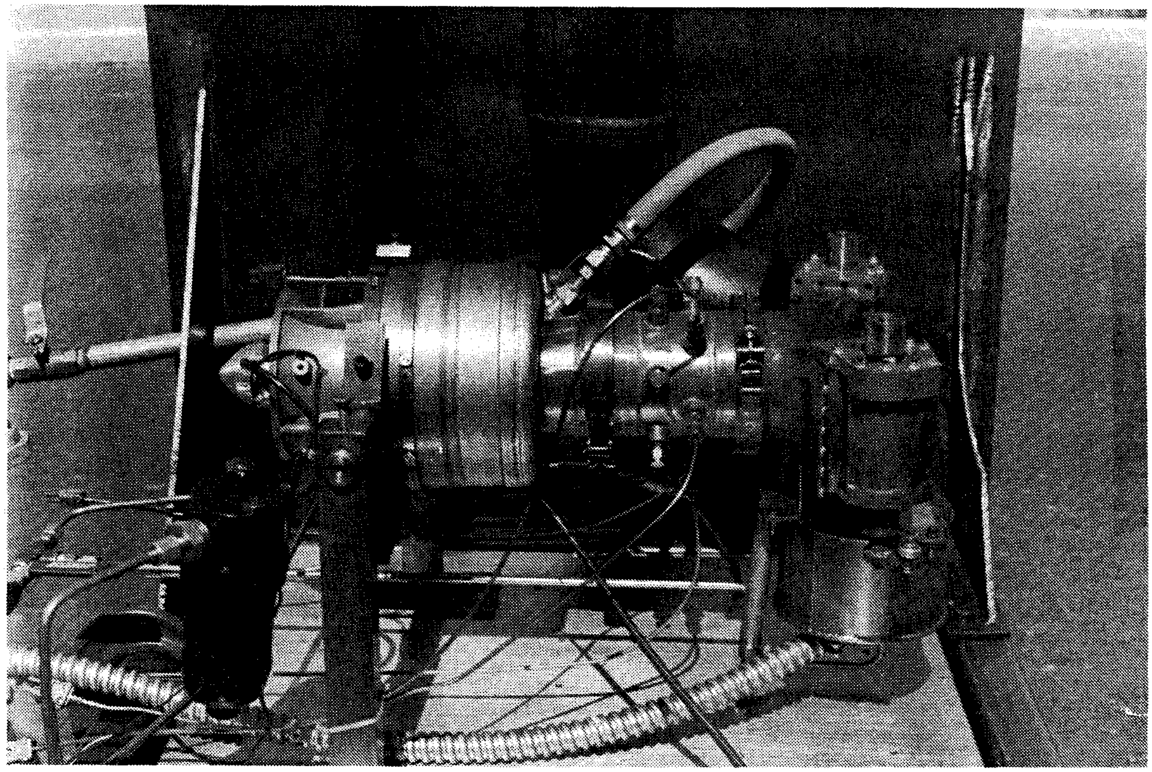


Figure 4 - Side view of engine and reverser showing mounting arrangement and instrumentation section.

7.3 Deflector Plates

The deflector plates were machined from solid plate stock as follows:

1. Pieces were laid out and cut from plate.
2. Pieces were then cold formed in a hydraulic press into a curved shape that approximated the final shape.
3. The pieces were then stress relieved.
4. The formed pieces were welded vertically to a platform that was bolted to a milling table.
5. Parts were finish machined to the final gaspath shape.

Sheet metal top and bottom pieces were welded to the deflector plates. Pivot shafts were then inserted into pilot holes and welded to the top and bottom pieces.

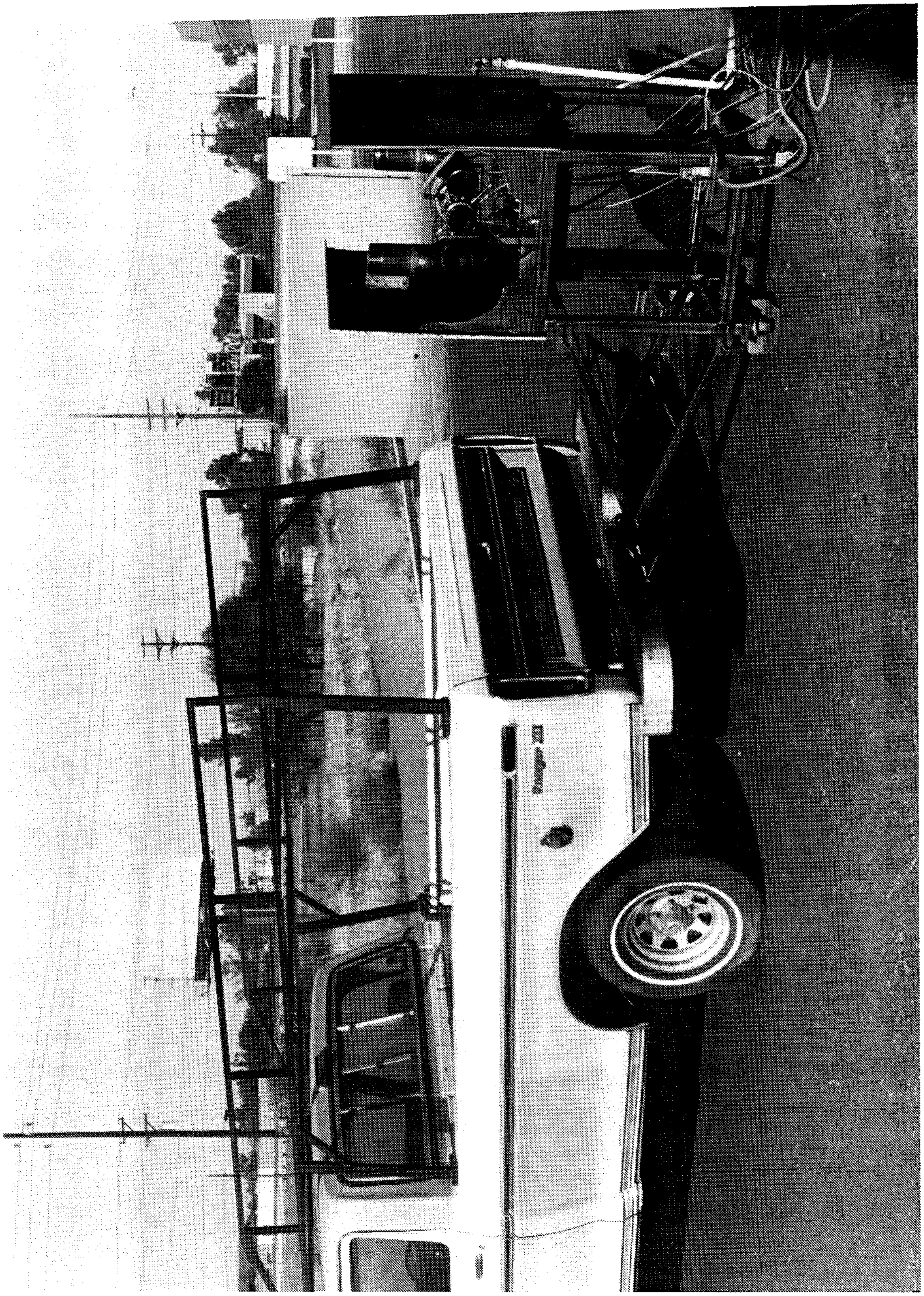


Figure 5 - Test stand and anchor vehicle

7.4 Graphite Bearings

Graphite bearings were turned from EDM bar stock. Bores were drilled and reamed. The bearings were then slit using a slitting saw on a milling machine to provide a controlled fracture site.

7.5 Engine Modifications

Engine modifications consisted of removal of the existing bifurcated exhaust duct and installation of a V-band flange. All sheet metal forming was done by hand. The V-band flange was machined from bar stock. This configuration can be seen in Figure 4.

To simplify lubrication and control requirements, the engine-mounted fuel pump was removed and a remote electric pump was used to supply fuel under pressure to the control stand. From the control stand, flexible hoses conducted fuel to the engine. A machined aluminum plug was installed in place of the engine-mounted pump to seal the pump and bearing cavity.

7.6 Test Fixtures

A cold-flow test fixture was fabricated from stainless-steel sheet. Pieces were cut from 0.040 flat stock and rolled and welded to form the plenum and ducts. Flex hoses were used to conduct the air from the electric blowers to the plenum. A static pressure port was installed in the plenum to record deviations in static pressure throughout operation from full forward to full reverse thrust.

8.0 TESTING

Testing consisted of engine testing and cold-flow bench testing. Engine testing was conducted outdoors approximately 25 feet from the rear facility door. This permitted use of facility air and electricity while maintaining a safe distance between the building and engine for fire protection. The operator was seated at the engine control panel approximately 25 feet from the engine. Figure 5 is a photograph of a typical test setup.

Prior to each test run, instrumentation and shut down systems were calibrated using a signal generator and thermocouple voltage source. Before and after each test, the thrust stand was leveled and the load cell was calibrated in both directions using dead weights. Figure 6 depicts the calibration set up.

Due to the expendable nature of the engine design, run time was minimized to reduce probability of hardware failure. Data were recorded immediately upon reaching the desired setpoint.

8.1 M-DOT Test Facility

The test facility consists of thrust stand, control stand, and fuel delivery system.

The thrust stand uses a 500 lb. capacity strain-gage load cell to measure the force applied in the forward or reverse direction to a hinged platform. Accuracy is ± .1 % F.S or ± 0.5 lb. The platform was designed so that it could be leveled independently of the frame for zeroing the thrust reading prior to test. The stand is portable to allow remote testing. Scatter shields were used to prevent injury in case of catastrophic engine failure.

Control stand instrumentation readouts consist of:

- Three factory-calibrated analog pressure gauges with an accuracy of ± 0.25 % F.S.

- Four calibrated digital temperature indicators with an accuracy ± 0.9° F.

- One digital frequency indicator with an accuracy of ± 1 least significant digit (LSD) or ± 2 ppm of input. This was used to measure engine speed and to operate the overspeed shutdown system.

- One digital thrust meter with an accuracy of ± 0.05% of reading or ± 1 count.

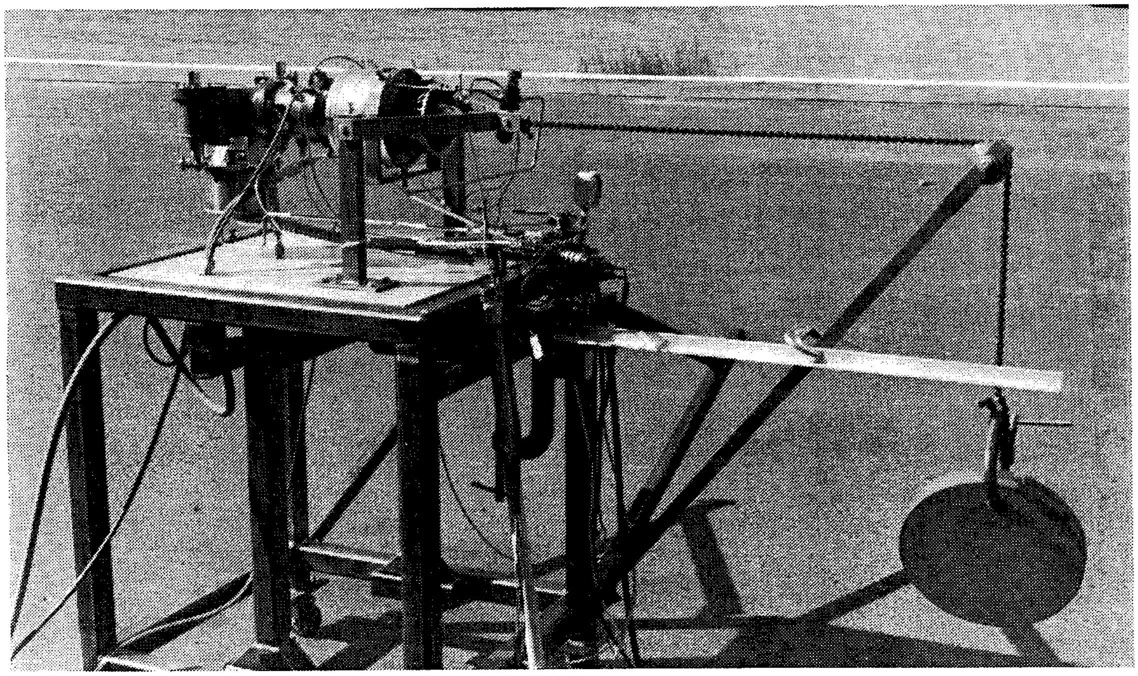


Figure 6 - Calibration of thrust stand.

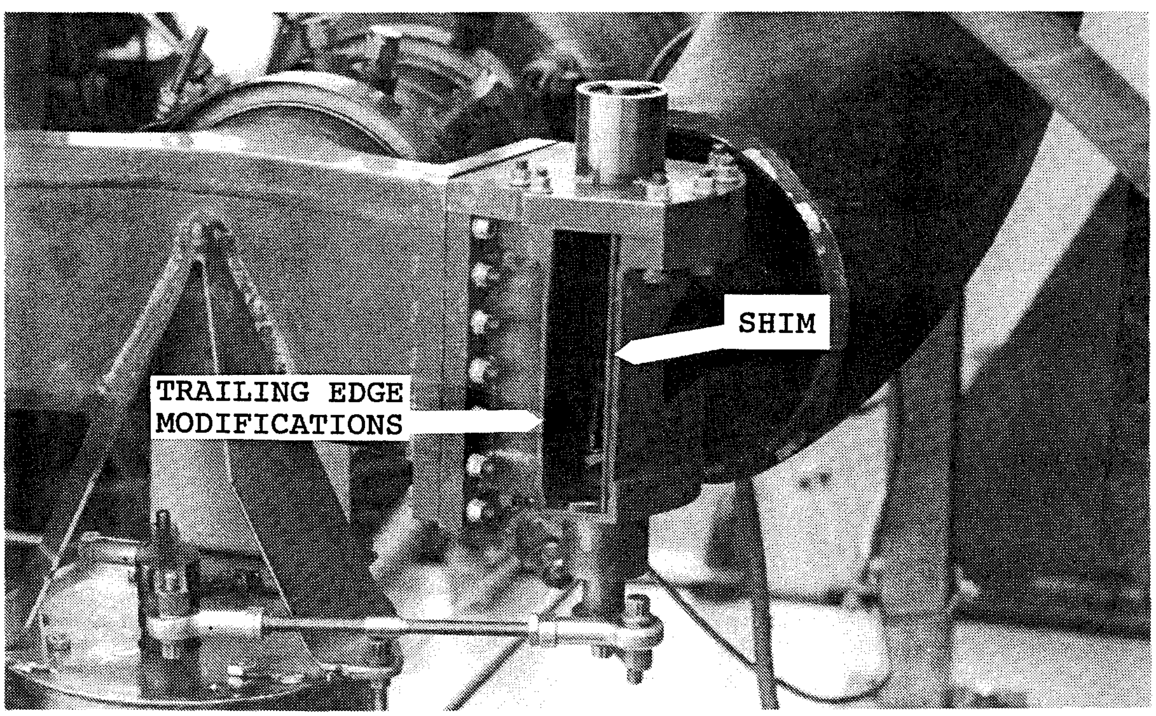


Figure 7 - Close up view of nozzle exit showing trailing edge modifications and sheet metal shim installed.

The test stand has four emergency engine shut-down systems: turbine overtemperature, mainshaft bearing overtemperature, engine overspeed, and low oil/air mist lubrication pressure. The stand is also equipped with five Hoke needle valves to manually control fuel flow. Fuel flow rate can be monitored using calibrated turbine flow meters. However, fuel flow data was not required for this program.

The fuel delivery system consisted of a 55-gal drum (with casters), 1/3 hp electric motor, 90 gph pump, relief valve, pressure gauge, and 20 micron filter. This unit was positioned 20-30 feet away from the engine and operator during testing. It provided a fuel pressure of 120 psig.

8.2 Instrumentation

In addition to the test stand thrust cell, the following performance instrumentation was used for testing:

One type K (chromel-alumel) thermocouple at station 1.0 to measure total temperature.
Four type K thermocouples at station 5.0 to measure total temperature.
One static pressure tap at the combustor plenum (station 3.0).
Four static pressure taps at station 5.0.
Engine shaft speed magnetic pickup.

In addition to the above, type K thermocouples were installed on the aft mainshaft bearing outer race as a safety precaution to alert the operator of impending bearing failure.

8.3 Engine Operating Limits

The following operating limits were observed during testing:

Engine speed -	102,000 rpm
Turbine exit temperature -	1720°F
Mainshaft bearing temperature -	200°F
Air/oil pressure -	20 psig. minimum

8.4 Engine Starting and Operation

Engine starting was accomplished as follows:

- Air pressure in the compressor tank was brought to 175 psig.
- Air flow to the bearing lubrication and servo cooling system was turned on and an assistant to the operator monitored the oiler to verify oil flow prior to start initiation.
- On a signal from the operator, an assistant would open the ball valve at the compressor receiver and spool the engine.

- The test stand start system would then automatically turn on the master fuel solenoid and ignition when engine speed reached 5000 rpm.

- The operator would open the engine fuel valve, await ignition and modulate fuel flow to bring the engine to idle.

- The assistant would then close the ball valve slowly as the engine approached idle speed. If a deceleration or hung start occurred, the air valve was reopened until idle speed was reached.

During a typical test run, the operator controlled engine speed, by modulating a twelve-turn needle valve.

On the initial test run with the prototype engine, flame-out was experienced during acceleration from idle. This generally occurred between 40,000 and 45,000 rpm. It was thought that a fuel port in the combustor manifold was plugged so the manifold was purged of fuel and blown out with air at 80 psi. When this didn't appear to recify the problem, engine S/N 55820 was substituted and testing was successfully completed.

8.5 Engine Baseline Testing

After conducting reverser testing, the engine was run with a calibration nozzle supplied with the engine to establish baseline thrust. Thrust was measured at the following conditions:

Shaft speed	100,000 rpm.
Engine inlet temperature	87°F
Barometric pressure	28.64 in. Hg.

The final baseline corrected thrust value of 95.4 lb was used for calculating reverser nozzle efficiency.

8.6 Reverser Testing

8.6.1 Cycling - Reverser operation was tested initially at low engine speed and power. The method was to cycle the reverser at progressively higher power settings until lock up due to warpage or differential expansion occurred. The test would then be aborted and the reverser disassembled and hand finished using a die grinder to remove material under witness marks. Reverser operation at full power was achieved on the 5th day of testing. Throughout testing, forward and reverse thrust was recorded.

8.6.2 Backpressure Variation - Engine speed, exit temperature and station 3.0 pressure were measured at several points throughout the cycle in order to quantify the nozzle effective area change. Data were recorded at full forward, full reverse and at 3 intermediate settings.

8.7 Bench Testing

Cold-flow bench testing was conducted to evaluate reverser operation prior to engine installation. The reverser was installed on the rig using a V-band clamp. Operation of the reverser was observed with cold air at approximately 3.0 in. H_2O total pressure flowing through it. During this test, areas of leakage around the deflector plate were identified and rectified.

After engine testing the reverser was tested to measure cycle speed. To do so, the unit was cycled from stop to stop five times and elapsed time measured with a stop watch.

8.8 Test Summary

Total Run time (Engine S/N 55820)	51 minutes
Total Starts	21
Time at or above 1650°F turbine-exit temp.	3.6 minutes
Estimated time at or above 100,000 rpm.	7.6 minutes

9.0 DATA REDUCTION AND TEST RESULTS

Hand calculations were done to correct performance to sea level standard day conditions.

9.1 Baseline Engine Performance

Measured and corrected performance for the baseline engine run is as follows. The delta correction factor is based on a local barometric pressure of 28.64 in. Hg. at the time of testing.

TABLE I

Speed (RPM)	*Measured Thrust (lb)*	*Corrected Thrust (lb)*	*Engine-inlet Temperature*	*Turbine-exit Temperature*
70K	24.4	25.5	547 °R	1428°R
80K	39.3	41.1	547 °R	1560°R
90K	60.3	63.0	547 °R	1736°R
100K	91.3	95.4	547 °R	1988°R

9.2 Reverser Performance

Reverser forward and reverse corrected thrust versus engine speed is presented below in Figure 8. Data presented is from testing conducted on 9-16-93 after the final nozzle area had been set. It should be noted that leakage around the deflector plates was not accurately measured. Performance on future reversers should improve with the employment of better sealing methods.

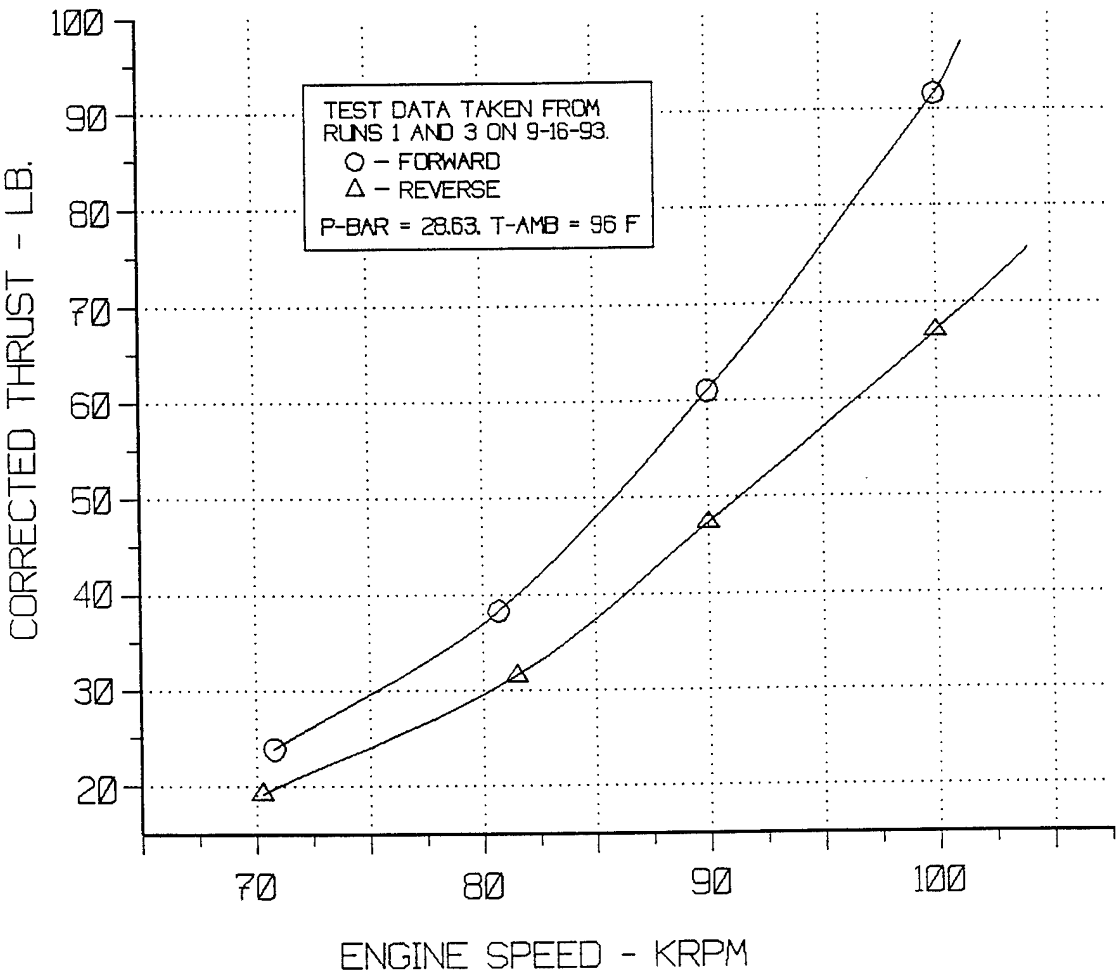


Figure 8 - Reverser performance in final trimmed configuration

9.3 Cycle time

Measured cold cycle time was 0.5 seconds from stop to stop.

9.4 Effective area

Recorded cycle data was used to calculate effective exit area using the following algorithm:

1. Operating points were located on a compressor map using measured P_3 and N values.

2. Compressor work was calculated.
3. Station 5.0 total temperature was calculated.
4. Station 4.0 total temperature was calculated.
5. Station 5.0 pressure was calculated using temperature ratio and known turbine efficiency.
6. Use station 5.0 pressure to calculate exit Mach No. and total flow function.
7. Use flow function to calculate effective exit area of nozzles.

This analysis procedure produced credible results. The calculated value of 4.766 sq. in. at position 1 corresponds well to the physical area (at temperature) of 4.71 sq. in. on the Sundstrand calibration nozzle (Slightly over 1% error). The calculated effective area values are accurate between themselves and are thus useful for identifying trends and relative changes.

The maximum calculated deviation in effective nozzle area was 2.8%. Figure 9 below is a plot of percent change in exit effective area versus reverser position.

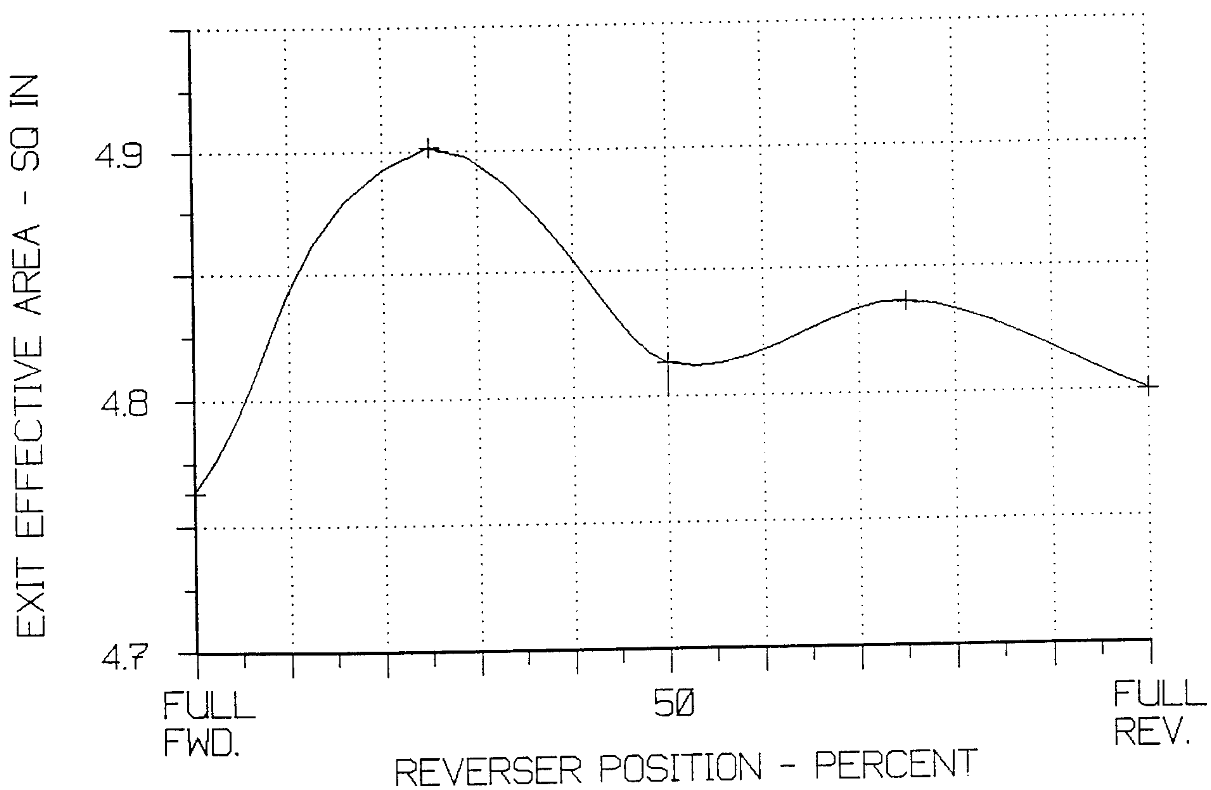


Figure 9 - Calculated nozzle back pressure versus reverser position

9.5 Hardware Durability

The reverser performed admirably. Operation was quick and smooth even at high thrust settings once the points of interference were removed.

The servo system experienced two failures. Failure of the motor amplifier board occurred early in the test phase. Until a new board was procured, the reverser was controlled by directly wiring 12 VDC power to the motor via a cross-wired double-pole double-throw momentary toggle switch. A test assistant would actuate the reverser by depressing the switch in the appropriate direction until full travel was reached. Failure of the motor commutator due to overheating also occurred. The motor was disassembled and the commutator leads resoldered. The motor was given additional cooling air and functioned normally thereafter.

10.0 PHASE II REVERSER LAYOUT

The final Phase I program task was to create a proposed layout for a flight-weight reverser to be used on a tactical missile similar to the FOG-M. A layout of the original missile power module was obtained from Sundstrand and used as a starting point. A complete self-contained power module was designed that incorporated engine, air inlets, cowling, fuel bladder, fuel delivery system, electronic engine control, electronic servo control and battery.

Modifications to the original configuration are as follows:

- The original exhaust duct was removed and replaced with the reverser duct. This duct is integral with the TJ-90 combustor plenum.
- The start cartridge has been moved sideways from its present location on the engine centerline behind the exhaust duct. This has been done to make room for the servo actuator.
- A servo actuator has been added to actuate the reverser deflector plates.
- An electronic control has been added. This will likely be a generic control containing a speed governor, start logic, logic to process input from the airframe control and an output command signal for the reverser servo control.
- An electronic servo control and motor amplifier. This has been placed in an enclosure separate from the main electronic control for two reasons:

1. To allow use of a generic engine control.
2. To reduce the size of both electronic enclosures allowing them to fit within the cheek fairings.

- Cowl cheek fairings have been added to the airframe immediately behind each inlet to provide bay area for the electronic engine control, servo control/amplifier and the servo battery. These also serve as fairings for the bluff exit nozzles. Stainless steel or refractory metal heat shields will be attached to the fairings where required to protect them from reverser jet blast.

- A battery has been added to provide power to the servo actuator. This will preclude having to increase capacity of the airframe battery and will allow voltage to be optimized for the rare-earth actuator motor.

Figure 10 is a top view of the proposed installation.

1

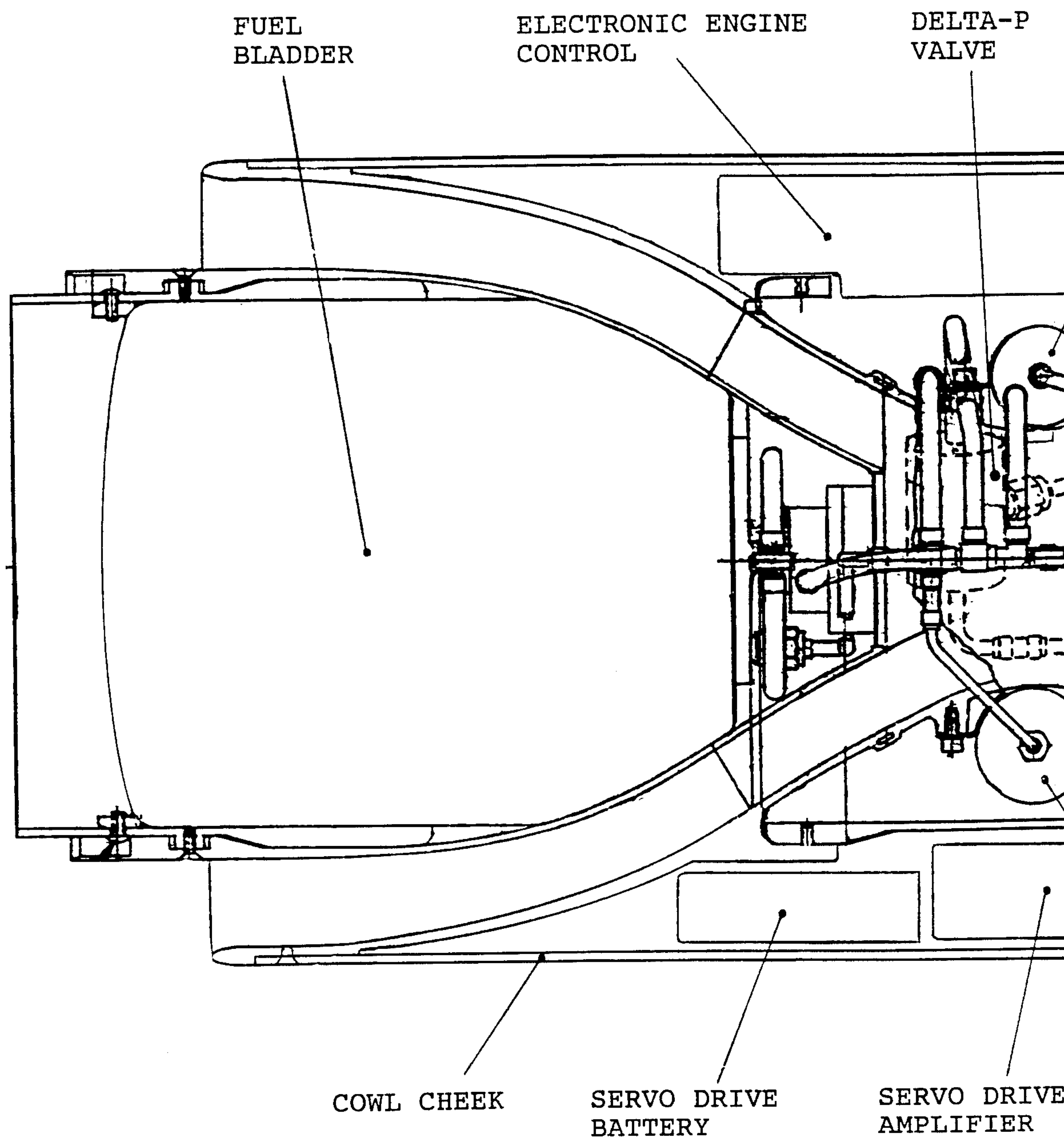
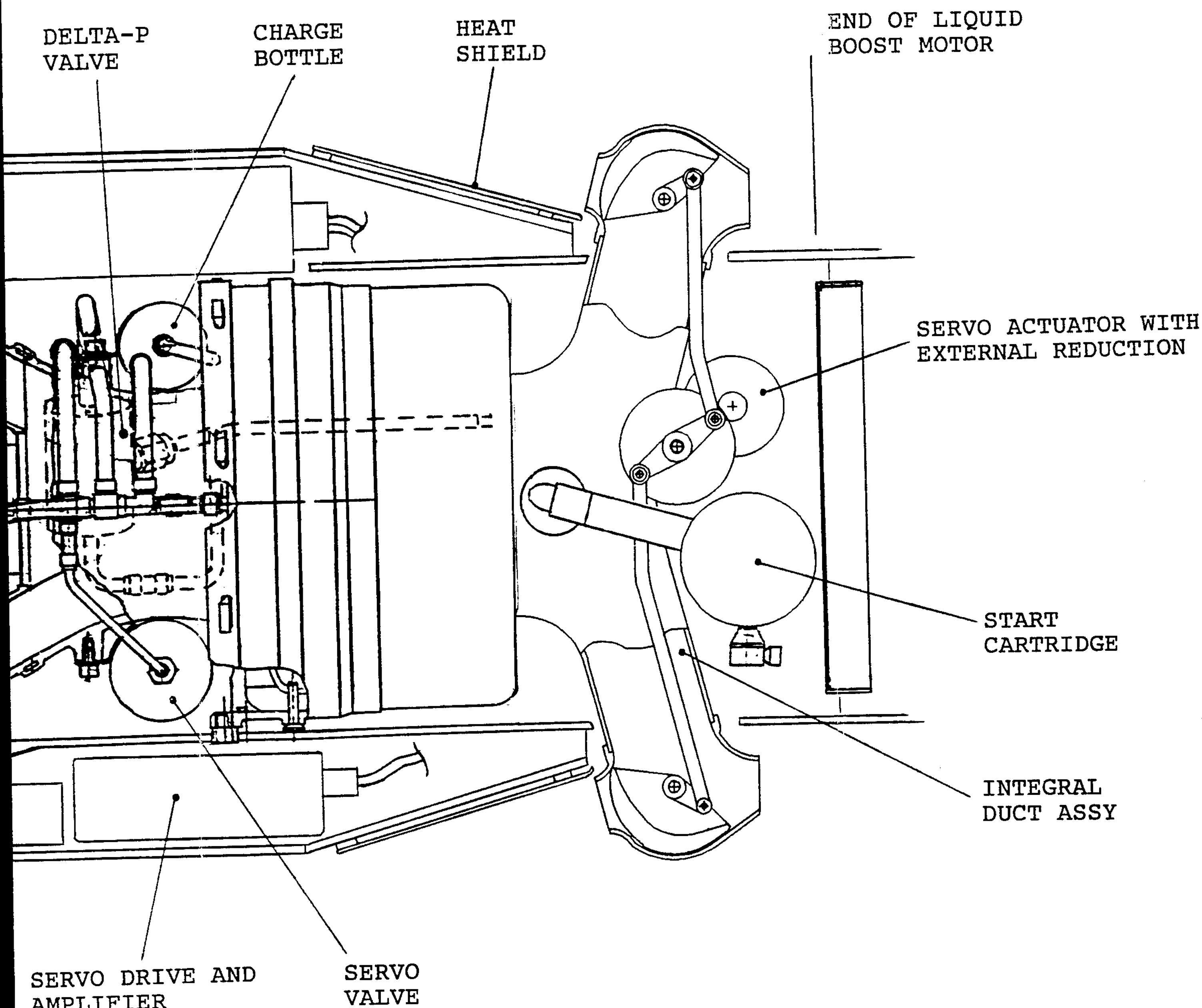


Figure 10 - Layout of proposed f
reverser.

②



of proposed flight-weight power module with

APPENDIX A - RAW TEST DATA

M-DOT INC.

QUALIFICATION TEST LOG

ACCT. No. 9108.003	Date 9/1/93	Test Fac. Cold flow stand
Assembly No. —	Model TJ-90 w/REVERSER	Unit Serial No. —
Engineer SHREINER	Technician	Supervisor Seegers
Test Type Cold Flow Bench Test	Customer MICOM	Build No. —

Start Time	Stop Time	Hours	Starts	REMARKS ZERO = 141"
				PRESSURE DROP "H_2O
				Fwd THRUST 142 1/2 139 7/16
				Rvrs THRUST 142 1/2 139 3/8
				1/16" PRESSURE (–) SPIKE during (Cycling) TRANSITION
				FROM Fwd TO REVERSE

SUMMARY: Total Operating Time N/A hrs. — min. Ref. Data Page

Total Manual Starts —

Total Automatic Starts — ENGINEERING

M-DOT INC.

T_{amb} = 92 **QUALIFICATION TEST LOG** P_{BAR} = 28.77

ACCT. No. 9108.003	Date 9/11/93	Test Fac. —
Assembly No.	Model TJ-90 Prototype	Unit Serial No. Prototype
Engineer Shreiner	Technician Shreiner	Supervisor
Test Type Reverser Cycling	Customer US ARMY	Build No. —

Start Time	Stop Time	Hours	Starts	REMARKS
9:58	10:00			RUN #1
				74.4 1072 308
				3.2 PSI 19.5
				#5 3
				N T_5 P_5 T_3 P_3
9:58	10:00			74.4 1072 3.2 308 19.5
				- Bringing throttle up & engine sounded
				like it was surging or combustor instability
				& blew out around 75K
				- Started on 1st try
				- Reverser would not cycle after
				engine was shut-down

SUMMARY: Total Operating Time ____ hrs. ____ min. Ref. Data Page ____

Total Manual Starts 2

Total Automatic Starts 0 ENGINEERING ____

M-DOT INC.

T_{amb} = 92 **QUALIFICATION TEST LOG** P_{BAR} = 28.77

ACCT. No. 9108.003	Date 9-11-93	Test Fac. —
Assembly No. —	Model TJ-90 Prototype	Unit Serial No. Proto.
Engineer Shreiner	Technician Shreiner	Supervisor —
Test Type Cycling + Perf.	Customer US Army	Build No. —

Start Time	Stop Time	Hours	Starts	REMARKS
				Run #2
10:16	10:18			N T_5 P_5 T_3 P_3 T_{BRG}
		36.3		88.6 1127 4.0 361 28
				90.
				Got up to 90 K RPM and
				Engine blew out T_5 ≈ 1287
				- Compressor instability @ 72 KRPM

SUMMARY: Total Operating Time ____ hrs. ____ min. Ref. Data Page ________

Total Manual Starts 1

Total Automatic Starts 0 ENGINEERING ________

M-DOT INC.

$T_{amb} = 92 F$ **QUALIFICATION TEST LOG** $P_{BAR} = 28.76$

ACCT. No. 9108.003		Date 9/14/93		Test Fac. M-DOT INC	
Assembly No. —		Model TJ-90 / SN 55820-170316-100 RUA		Unit Serial No. 55820	
Engineer SHREINER		Technician SHREINER		Supervisor	
Test Type TJ-90 w/REVERSER		Customer MICOM		Build No. —	

Start Time	Stop Time	Hours	Starts	REMARKS
				PLAN I 70K, 80K, 90K BASELINE w/REVERSER
				PLAN II 70K REVERSE THRUST 80K, 90K, ...
RUN #1				T N T_5 P_5 T_3 P_3 T_{BRG}
				21.9 71.2 919 2.5 291.6 19 145
				34 80.4 1015 4.0 345 25.5 157
3:58	4:01			ENGINE S/D SPONTANEOUSLY AS IF FUEL WAS CUT OFF
				CHANGED LUBRICATOR
RUN #2				T N T_5 P_5 T_3 P_3 T_{BRG}
4:24				52.7 90.5 1145 7 412 36 202
		REVERSED		@ 70 70K 925 2 291 17 184
				80K 974 3.2 348 25.5 197
				90.1 1058 5.6 405 36 207
			4:29	THROTTLE BACK TO 70K TO OPERATE
				REVERSER MULTIPLE TIMES
			REV	71.5 928 2 297 17.5 195
	4:32			

SUMMARY: Total Operating Time — hrs. 15 min. Ref. Data Page

Total Manual Starts 4

Total Automatic Starts — ENGINEERING

M-DOT INC.

T_{amb} = 92 F

QUALIFICATION TEST LOG

P_{BAR} = 28.76

ACCT. No. 9108.003	Date 9/16/93	Test Fac. M-DOT INC.
Assembly No. —	Model TJ-90 -100 RJ A	Unit Serial No. 55820
Engineer SHREINER	Technician SHREINER / SHERBECK	Supervisor —
Test Type TJ-90 W/REVERSER	Customer MICOM	Build No. —

Start Time	Stop Time	Hours	Starts	REMARKS
			Plan#	70K 80K 90K
RUN#	3			T N T_5 P_5 T_3 P_3 T_{BRG}
4:45				55.2 90.8 1188 7.5 414 38 206
	4:48			MANUAL SHUT-DOWN — TUNING NOZZLE TO
				ACHIEVE MAX THRUST 65-74 lb T_5 - 1260-1360
RUN #4				T N T_5 P_5 T_3 P_3 T_{BRG}
5:05	5:06			58 90.8 1267 8.1 423 38.5 212.5
				NOTES:
				1) FROM PREVIOUS RUN, ENGINE WAS CHANGED-OUT
				2) REVERSER VECTORING VANES REWORKED TO PREVENT
				SEIZING-UP

SUMMARY:

Total Operating Time — hrs. 15 min.

Ref. Data Page ________

Total Manual Starts 4

Total Automatic Starts —

ENGINEERING ________

M-DOT INC.

T_{amb} = 96 F **QUALIFICATION TEST LOG** P_{BAR} = 28.63

ACCT. No. 9108.003	Date 9/16/93	Test Fac. M-DOT INC.	
Assembly No. —	Model TJ-90 w/ REVERSER	Unit Serial No. 55820	
Engineer SKREINER	Technician SKREINER	Supervisor SEEGERS	
Test Type TJ-90 w/ REVERSER	Customer MICOM	Build No. —	

Start Time	Stop Time	Hours	Starts	REMARKS
TEST	PLAN	—		1ST RUN – 90K CHECK T_5, P_5, & T
				PARAMETERS TO MEET T_5 => 1360°F T >
RUN #1				T N T_5 P_5 T_3 P_3 T_{BRG}
1:57			Fwd	63 90.6 1427 10.2 423.3 39.5 219.8
			Fwd	39.5 80.4 1230 6.0 366. 26.5 210
		2:02	Fwd	26.0 71.0 1102 3.6 309 18.9 200
				— MANUAL SHUT-DOWN
	TEST	PLAN II		2ND RUN – 70K CYCLE TAKE DATA REPEAT
				80, 90, 100K ALL REVERSE
				T N T_5 P_5 T_3 P_3 T_{BRG}
3:45	3:51		Rev	19.2 70.1 1017 3.1 302 18. 185
			Rev	31.5 80.5 1143 5.2 362 26.5 206
			Rev	47.4 90.0 1339 8.4 430 37.0 224
			Rev	63 100.0
				BRG OVERTEMP SHUT-DOWN

SUMMARY: Total Operating Time — hrs. 25½ min. Ref. Data Page

Total Manual Starts 10 MANUAL

Total Automatic Starts

ENGINEERING

MANUAL SHUT-DOWNS 7

M-DOT INC.

Tamb = 96 F **QUALIFICATION TEST LOG** PBAR = 28.63

ACCT. No. 9108.003	Date 9/16/93	Test Fac. M-DOT INC.
Assembly No.	Model TJ-90 S/N 55820-170316-10C	Unit Serial No. 55820
Engineer SHREINER	Technician SHREINER	Supervisor SEEGERS
Test Type TJ-90 w/REVERSER	Customer MICOM	Build No. —

Start Time	Stop Time	Hours	Starts	REMARKS
		TEST	PLAN	— 100K REVERSE TAKE DATA — down to 80 cycle, 90 cycle, 100 cycle
RUN # 3				T N T5 P5 T3 P3 TBRG
		2:00	REVERSE	67 100 ~~1872~~ 1572 14 520 53 238.9
				— Shut-down — MANUAL — REVERSER VANE JAMMED
RUN # 4			TEST	PLAN — 100K REVERSE — TAKE data
4:46				Reduce to 80K cycle, 90K cycle, 100 cycle
				T N T5 P5 T3 P3 TBRG
	4:47			78 100
			—	Shut-down — possibly TBRG ≥
RUN #5			N	TFWD TREV
4:55	4:56		80	40.0 33.2
			90	65.0 43.8
				— MANUAL shut-down

SUMMARY: Total Operating Time See page hrs. 1 of 4 min. Ref. Data Page ______

Total Manual Starts See Page 1

Total Automatic Starts ______ ENGINEERING ______

M-DOT INC.

QUALIFICATION TEST LOG

Tamb = 96 F P_{BAR} = 28.63

ACCT. No. 9108.003		Date 9/16/93		Test Fac. —	
Assembly No. —		Model TJ - 90		Unit Serial No. 55820	
Engineer Shreiner		Technician Shreiner		Supervisor —	
Test Type Performance		Customer US Army		Build No. —	

Start Time	Stop Time	Hours	Starts	REMARKS
Run	#6			90 cycle 100 cycle
6:33	6:34			
				↑ N T_5 P_5 T_3 P_3 T_{BRG}
				100
				– ENGINE Blow-out – 100K
				T_5 shut-down
Run #7				↑ N T_5 P_5 T_3 P_3 T_{BRG}
		3min Run		78.9 ~~100~~ 93.8 1678 12.5 462 44 217
				– MANUAL shut-down –
Run #8				↑ N T_5 P_5 T_3 P_3 T_{BRG}
		1 min		100
				98K 1650°F
				– MANUAL Shut-down
				– Bent tab straight (Opened EXIT AREA for Run #8)

SUMMARY: Total Operating Time — hrs. — min.   Ref. Data Page ______

Total Manual Starts See page 1 of 4

Total Automatic Starts ______   ENGINEERING ______

M-DOT INC.

Tamb = 96 F **QUALIFICATION TEST LOG** Pbar = 28.63

ACCT. No.	9108.003	Date	9/16/93	Test Fac.	—
Assembly No.	—	Model	TJ-90	Unit Serial No.	55820
Engineer	Shreiner	Technician	Shreiner	Supervisor	—
Test Type	Perf.	Customer	U.S. Army	Build No.	—

Start Time	Stop Time	Hours	Starts	REMARKS
Run	#9	1½ min		– OPENED AREA MORE
				Π N T5 P5 T3 P3 TBRG
				98.5 1650°F – MANUAL Shut-down
Run	#10			Π N T5 P5 T3 P3 TBRG
6:53		4 min	Fwd	91.6 100 1611 14.5 524 53 237
			Fwd	61 90 1385 8.5 432 37.5 217
			Fwd	38.3 (38.3) 80.7 1175 5.0 361 26.3 204
	6:57		Fwd	23.8 70.8 1064 3.0 307 17.7 190.9
				– MANUAL Shut-down
				POST TEST STAND Cal
				REV. THRUST Fwd THRUST
				WEIGHT READING WEIGHT
				53.0 54.5 53 56.4
				93.0 95.4 93 97.1

SUMMARY: Total Operating Time See page 1 of 4 hrs. ____ min. Ref. Data Page ____

Total Manual Starts See page 1 of 4

Total Automatic Starts ____ ENGINEERING ____

M-DOT INC.

T_{amb} = 87 F **QUALIFICATION TEST LOG** P_{BAR} = 28.64

ACCT. No. 9108.003	Date 9/18/93	Test Fac. M-DOT INC
Assembly No. —	Model TJ-90	Unit Serial No. 55820
Engineer Shreiner	Technician Shreiner	Supervisor Sievers
Test Type TJ90 BASELINE	Customer MICOM	Build No. —

Start Time	Stop Time	Hours	Starts	REMARKS
Run #2				BASELINE with SUNDSTRAND NOZZLE
				70, 80, 90, 100K DATA
5:57	6:00			T N T_5 P_5 T_3 P_3 T_{BRG}
				24.4 70. 968 2.9 283 18.3 190
				39.3 80 1100 4.8 347 26.4 203
				60.3 90 1276 7.9 412 37.6 216
		3 min		91.3 100 1528 12.6 508 52.0 250
				Delta Corr = $\frac{28.64}{29.92}$ = .957

SUMMARY: Total Operating Time — hrs. 3 min. Ref. Data Page

Total Manual Starts 1

Total Automatic Starts 0 ENGINEERING

M-DOT INC.

Tamb = 95 **QUALIFICATION TEST LOG** P_{BAR} = 28.71

ACCT. No. 9108.003	Date 9/24/93	Test Fac. M-DOT INC.
Assembly No. —	Model TJ-90	Unit Serial No. 55820
Engineer Shreiner	Technician Shreiner	Supervisor Seegers
Test Type Reverser Cycling	Customer MICOM	Build No. —

Start Time	Stop Time	Hours	Starts	REMARKS
				START ENGINE CYCLE @ 100K RPM
10:30	10:31		#1	over temp
10:33	10:35		#2	40-50 Flame-out
10:40	10:41		#3	43K Flame-out
				— Blew compressed air through fuel manifold
11:10	11:12		#4	did not cycle @ 100K
				70 – 90K it cycled
				— mod to top plate & BRG
2:43	2:46		#5	Cycled @ 100K 3 times – successfully
			#6	5 point
				N T5 P3
3:45				~~95K~~ 95K 1350 45 POSITION 1
				99.5 1309 47.5 2
				97.7 1368 47 3
				97.8 1382 46 4
		3 min		95.0 1482 43 5

SUMMARY: Total Operating Time ____ hrs. 12 min. Ref. Data Page ____

Total Manual Starts 6

Total Automatic Starts 0 ENGINEERING ____

M-DOT INC.

QUALIFICATION TEST LOG

ACCT. No. 9108.003	Date 10/3/93	Test Fac. M-DOT INC.
Assembly No. —	Model —	Unit Serial No. —
Engineer Shreiner	Technician Shreiner	Supervisor Seegers
Test Type Cold Flow	Customer MICOM	Build No. —

Start Time	Stop Time	Hours	Starts	REMARKS
				Cycle TIME
				10 cycles 5 SEC
				REVERSER WEIGHT
				12.5 lbs

SUMMARY: Total Operating Time ______ hrs. ______ min. Ref. Data Page ______

Total Manual Starts ______

Total Automatic Starts ______ ENGINEERING ______